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RESEARCH ARTICLE

Determinants of access to animal health care in France: evidence from a spatial econometric framework

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Abstract

Over the last two decades, concerns have arisen in the veterinary profession about the declining number of food animal veterinarians. Based on a One Health perspective which recognizes that the health of people, animals, and their environment are interconnected, the French policymakers implemented a set of policies to combat the veterinarian shortage in the food animal sector that may cause public health crises. However, public interventions are unlikely to succeed in combating the veterinarian shortage unless they are preceded by a relevant understanding of the main determinants underlying this shortage. This paper contributes to identifying the main factors of the veterinarian shortage in 2019 in the French cattle sector using databases that integrate French veterinary clinics, farm characteristics and socio-economics features, and a spatial econometrics framework. Our results highlighted, first, strong and positive spatial autocorrelation in terms of veterinarian shortage between observations. Second, favorable socio-economic characteristics of a region were associated with a reduction in veterinarian shortage. Third, proximity to urban regions was associated with a decreased veterinarian shortage. Based on these findings, we provided some recommendations to policymakers.

Keywords Animal health care accessibility · Spatial econometrics · Public policy · Veterinarian shortage

JEL Classification I18 · R19 · C31

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Introduction

Despite increasing numbers of veterinarians, the percentage practicing in the food animals sector (FAS) has declined. Currently, the veterinary profession is experiencing recruitment difficulties within the FAS across various countries, including Canada, the United States, and the European Union. Yet, veterinarians in FAS are critical in providing epidemiological surveillance of animal diseases, reducing zoonoses and ensuring availability and continuity of animal health care. This situation is characterized as a veterinarian shortage. However, this notion of shortage is not considered in this article in a purely economic sense, but rather from a public health perspective. In economics, a shortage is defined as a situation where the quantity demanded of a good or service exceeds the quantity supplied at a given price. In this article as established by regulators, policymakers, and veterinarians, the term shortage denotes a level of supply insufficient to meet the demand for care under optimal conditions.

The veterinarian shortage may cause major economic, social, and health crises. Firstly, it has long been established that diseases affecting farm animals substantially diminish societal benefits derived from the food chain (Mcinerney, 2004). Addressing the challenge of global food security necessitates a concerted effort by veterinarians to combat prevalent livestock diseases and their detrimental effects, ensuring availability, accessibility, and stability of the food supply for a given population. Veterinarians in the FAS must contend with food safety concerns arising from food-borne pathogens (Fitzpatrick, 2013). From an economic perspective, a veterinarian shortage in FAS may undermine farm profitability (Bennett, 2003). Secondly, veterinarians can reduce zoonosis that incurs harmful consequences, ranging from the herd to a macroeconomic scale in both developed countries (Boisvert et al., 2012) and developing countries (Randolph et al., 2005; Rich & Wanyoike, 2010). Thirdly, a veterinarian shortage in the FAS gives rise to animal welfare concerns, emerging as a societal issue (Grandin, 2014; Lagerkvist et al., 2011), as animals without adequate veterinary care may suffer or even die from diseases normally curable. Fourthly, the livestock sector is a key issue in problems related to land use, biodiversity, and climate change (Gerber et al., 2013; McMichael et al., 2007), which prompted the Food and Agriculture and Organization (FAO) to emphasize in a report that the livestock sector is "one of the top or three most significant contributors to the most serious environmental problems" (Steinfeld et al., 2006). Veterinarians, by helping and supporting producers implementing health care interventions aimed at decreasing the animal health loss envelope (gap in productivity) promote sustainable livestock practices that reduce greenhouse gas emissions and limit environmental degradation (Bernardo et al., 2021; Stephen et al., 2019).

The scope of the veterinarian shortage is presently being assessed in various countries. In a survey on the shortage of veterinarians in rural areas, among 28 European countries, 78.5% were currently experiencing a shortage of veterinarians (Federation of Veterinarians of Europe, 2020). Similarly, the United States is also contending with a shortage, particularly in the food animals sector (FAS)

(Wang et al., 2010), with 16 of 50 states having a shortage of rural veterinarians (Ouedraogo et al., 2018). Of the 21,000 veterinarians practicing in France, only one-third are engaged in the FAS. Further, 71% of veterinarians in FAS have a mixed practice (mainly food animals and companion animals).

Public authorities have warned about the veterinarian shortage alongside the physician shortage (*Après les déserts médicaux, les déserts vétérinaires*, 2020; Ministère de l'Agriculture et de la Souveraineté alimentaire, 2020). The French cattle, poultry, and swine sectors had 75, 90, and 98% respectively of *cantons*—administrative and territorial division that comprises several municipalities—in need of personnel (Berrada et al., 2022).

However, public interventions are unlikely to succeed in combating the veterinarian shortage in rural areas unless they are preceded by a relevant understanding of the main determinants and the mechanisms underlying this shortage (Humphreys et al., 2001). Failure to comprehend the root causes hinders the timely resolution of the problem, resulting in unnecessary expenditures. For instance, a study highlighted the ineffectiveness of a French public policy to combat the veterinarian shortage, indicating that policymakers have not targeted appropriate interventions (Berrada et al., 2024).

This paper aims to identify drivers of the veterinarian shortage in the French cattle sector using a spatial econometrics method. It will be valuable for enabling policymakers to understand underlying mechanisms and address the problem at its root. We focused on the cattle sector because cattle require individual medical attention, sometimes urgently, unlike other livestock sectors, and this sector represents 75% of expenditures on regulated diseases and 80% of revenue related to livestock (*L'activité des vétérinaires: de plus en plus urbaine et féminisée—Insee Première—1712* s. d., n.d.). In addition, we also proposed a list of recommendations.

Theoretical background

In recent years, the livestock farming sector has repeatedly encountered difficulties and economic crises (Hostiou et al., 2020). According to the 2020 Agricultural Census report, France has had a 30% reduction in specialized livestock farms over the last decade (Caraes, 2020). The crisis in agriculture and the livestock sector is causing deleterious effects on rural regions, given that their economic sustenance relies heavily on these sectors. Rural regions in many countries have similar outcomes due to centralization (Mahoney et al., 2001) and specific challenges, including travel conditions and a lack of public services (Delfosse et al., 2019), urban migration, and an aging population, which exacerbates this trend (Farmer et al., 2010). As a result, a clustering of farms is observed in several sectors (Dervillé & Allaire, 2014; Roguet et al., 2017). In parallel, the veterinary profession also exhibits a trend towards concentration. In recent years, younger veterinarians exhibit a distinct relationship with their work, prioritizing work-life balance (Analyse prospective des besoins de diplomes veterinaires en France, 2019; Andrus et al., 2006). Young veterinarians prefer to work as salaried employees to limit working hours. As a consequence, the proportion of veterinarians working as employees among new graduates in the private sector has significantly risen (Conseil national de l'Ordre des vétérinaires, 2021). Thus, the trend towards salaried practice appears to be taking hold for the long term, leading new veterinarians to seek employment in existing veterinary clinics (Truchet et al., 2017).

The economic geography literature highlighted how economies of agglomeration shape the geographical distribution of economic activities (Fujita et al., 2001; Henderson et al., 2001; Krugman, 1991). It aims to explain how the clustering of firms leads to lower transportation costs, proximity to a market, and knowledge sharing. The positive externalities generated lead to a cycle where regions become more attractive, drawing in more businesses and workers (Glaeser et al., 1992). From farmers' perspective, clustering can lead them working more closely together, sharing new farming techniques, negotiating better prices for supplies and products, and accessing markets more effectively. Therefore, veterinarians in FAS are incited to settle in regions where the concentration of cattle would provide a potential market. But the potential market is not the only factors of veterinarians' location. Olfert's research showed that veterinarians, who make location decisions that optimize their utility, are driven by several factors including proximity to urban centers, the quality of public services, the natural environment, and other aspects that enhance the quality of life (Olfert et al., 2012). The factors of veterinarians' location choice are similar for physicians in rural areas (Benarroch * & Grant, 2004). In human health care, Hurley (1991) and Bolduc et al. (1996) demonstrated that income and community size significantly influenced physicians' location choices. Other factors were proposed, including competitive remuneration (Grobler et al., 2015), adequate staffing and infrastructure (Garnett et al., 2008; Wilkinson et al., 2001), spousal opportunities, and urban amenities (Goetz & Debertin, 1996).

Studies on veterinary health care accessibility and its determinants are scarce (LaVallee et al., 2017). Olfert et al. (2012) and Truchet et al. (2017), who stand as exceptions, identified determinants of location choices of veterinarians as socio-economic factors and urban/rural amenities. However, Olfert and Truchet analyzed a veterinarian's choice to settle in a given area and addressed the veterinarian shortage from a supply perspective. Nevertheless, veterinarians' location does not necessarily mirror challenges faced by farms in accessing veterinary health care. Regions where veterinarians are scarce may not always experience a veterinarian shortage, as some regions without veterinarians have a minimal livestock population. Conversely, areas with a surplus of veterinarians may still struggle with health care access due to an inadequate supply relative to demand.

The shortage of health care requires a relevant measurement by taking into account both the supply and demand of veterinary health care. In the human health care domain, the majority of studies addressing access to medical care have focused on the combination of availability and accessibility, often referred to as spatial accessibility (Luo & Wang, 2003). This is the case of two-step floating catchment area (2SFCA) indicator, widely employed and discussed in the literature on accessibility to human health (Guagliardo, 2004; Khan & Bhardwaj, 1994; Park & Goldberg, 2021). In animal health care, Berrada et al. (2022) pioneered an indicator based on 2SFCA to quantify spatial accessibility to animal health in FAS in France.

Validated in an official decree (*Décret n° 2021–578,* 2021), it has become an established tool for analyzing spatial accessibility to animal health in FAS. This indicator will be used as the dependent variable in our econometric model.

Turning to independent variables, we identified three sets of factors from the literature cited above. The first set was related to the attractiveness of the territory, encompassing both urban-related facilities and geographical features (e.g., proximity to the sea and mountains) likely to attract veterinarians. The second set was socio-economic variables, including unemployment rate, average income in the region, and access to general practitioners. These features are crucial not only for sustaining livestock farmers in their activities, but also for the establishment of veterinarians and employability of their spouses. The third set pertained to the structure of supply and demand of veterinary health care. We considered demand factors including the number of livestock units, share of intensive large-scale cattle farming, and regional specialization in dairy or beef production. In addition, we also considered supply factors including the average size of veterinary clinics (the average number of veterinarians in all sectors per clinic) and proximity to the Belgian border—where a number of Belgian veterinarians practice. The Belgian border was used as a control variable in this model to reduce the influence on the relationship between independent and dependent variables. The effect of the average size of veterinary clinics was used to assess agglomeration effects, as larger structures may reduce production costs and improve veterinarians' ability to better provide care.

Hence, the present paper contributes to the literature by employing a 2SFCA indicator that considered both supply and demand. This indicator enables clear identification of farms exposed to difficulties in health monitoring and permanent care for food animals, thereby better meeting health care needs of rural livestock. Our second contribution is to use a spatial econometrics framework which enables the identification of spatial patterns, such as clustering or spillovers that non-spatial models might overlook. Using a database that integrates data from veterinary clinics, farms, and agricultural and socio-economic data, our analysis provided insights to understand the mechanisms underlying veterinarian shortage to inform targeted interventions.

Materials and methods

Data

Sources and construction of data are summarized in Fig. 1.

Dependent variable

Demand Cattle farms were extracted from the French National Bovine Database Identification 2019 (BDNI) and from SIGAL (Sanitary Information System). The BDNI database is managed by a specific office of the French Ministry of Agriculture and Food Sovereignty (MAFS) and has been used in several studies (Mayo et al., 2020; Raboisson et al., 2011). All animals, farms, and farmers in the cattle sector are

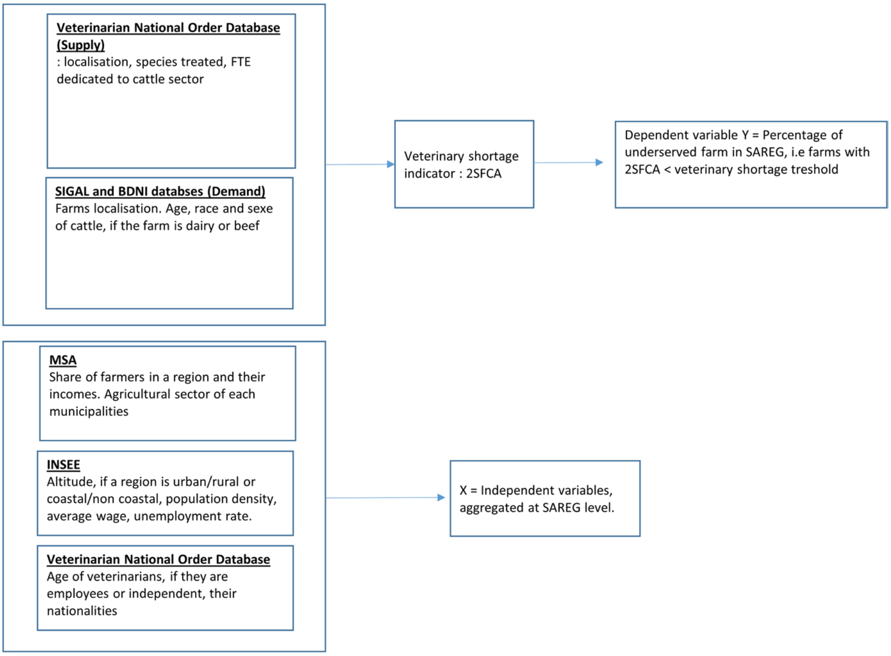

Fig. 1 Summary of the data construction process

individually identified. The BDNI contains, for all animals, an identification number, date of birth, sex, farm of birth, breed, and date of first calving (females only). These characteristics were used to compute livestock units (LU), which facilitates aggregation of livestock, taking into account the type of cattle (e.g., dairy or beef) and their age. Geographic coordinates and animal populations of all French cattle farms in the SIGAL database 2019 were provided by the General Directorate for Food (DGAL) of the MAFS.

Supply: veterinarian population To quantify the supply of animal health care, we used a dataset from the 2019 Veterinarian National Order Database, which includes the number of veterinarians, the species for which they provide service, and the geographic coordinates of where they practice. We estimated the percentage of full-time equivalent (FTE) dedicated to each sector for all veterinarians by using data from a previous survey (Sannier & Lhermie, 2020). In that survey, a total of 1457 veterinarians engaged in animal production were surveyed regarding their working hours, constituting a sample that represented 22.7% of the target population. These veterinarians provided information about the primary, secondary, and potentially tertiary animal species they treated. Using the species data declared by veterinarians in the national database, we extrapolated FTE at the cattle sector level.

Share of underserved farms In the present study, our dependent variable was defined as the proportion of underserved farms within a small agricultural region (SAREG) and can be expressed as:

$$y_i = \%\ of\ underserved\, farms\ in\ SAREGi = \frac{underserved\, farms\ in\ SAREGi}{total\ of\ farms\ in\ SAREG}i \quad (1)$$

where SAREG is a division of the French territory created by *Institut national de la statistique et des études économiques* (INSEE) and *Service statistique public* (SSP) to have an appropriate and consistent division of France into regions as homogeneous as possible from an agricultural perspective without being restricted by administrative boundaries.

To define an underserved farm, we adopted the French MAFS definition. According to this definition, a farm (denoted as *j*) is considered underserved in the cattle sector if < 1 full-time equivalent (FTE) dedicated to the cattle sector is available and accessible for 5000 livestock units (*Décret n° 2021–578*, 2021), that is if:

$$2SFCA_j < \frac{1}{5000}$$

where 2SFCA is the two-step floating catchment area, a spatial accessibility method. This method integrates both the supply and demand and takes into account the availability of the veterinary clinics and the accessibility of the veterinary clinics to the farms. It is computed following two steps. First, for each veterinary clinic, all livestock units (LU) of cattle that are within a travel time threshold from the clinic are summed, and then a FTE-to-LU ratio is computed for each clinic. This reflects the availability of each veterinary clinic depending on the nearby demand. Second, for each farm, the FTE-to-LU ratios (computed at the first step) within a travel time threshold are summed up, yielding the 2SFCA indicator calculated at the level of each farm. The travel time threshold is a catchment that represents the maximum distance covered by veterinarians in a given travel time by car. Based on a survey and a sensitivity analysis testing several catchment areas, veterinarians rarely travel beyond 45 min by car. Thus, we assume in this study that this is the maximum distance covered by veterinarians. For detailed information about 2SFCA calculation in the veterinary context, one can refer to this article (Berrada et al., 2022).

In this paper, we opted to calculate the proportion of underserved farms in a SAREG concerning veterinary care rather than, for instance, relying on average 2SFCA indicators. The rationale behind this decision is that the latter may have hidden disparities in access to care within a SAREG. To draw an analogy, it is like assessing the poverty rate in a specific area instead of relying on average salaries that do not capture the extent of disadvantaged people.

Hence, based on the 2SFCA indicator computed for each farm *j* and the definition of an underserved farm from MAFS, our dependent variable *y* for SAREG *i* can be expressed as:

$$y_{\mathrm{i}} = \frac{\text{\# farms underserved according to the French MAFS definition in SAREG } i}{\text{Total of farms in SAREG } i} \tag{2}$$

Independent variables

Concerning our independent variables, we used data provided by the *Mutualite Sociale Agricole* (MSA), the official French authority overseeing farmer health care and social security. Updated annually, this database offers comprehensive details on the French farm population, encompassing the proportion of farmers, their incomes, age, and the agricultural specialization of each municipality.

Geographical and socio-economic variables were derived from the INSEE database, including average population income, unemployment rate, and proportion of urban areas in a SAREG.

From these explanatory variables, we constructed three sets of variables. The first group was associated with characteristics of the territory and included variables such as the proportion of surface area classified as large urban areas, whether the SAREG is coastal, and average altitude. The second group pertained to socio-economics factors of the regions, comprising variables like the logarithm of the average hourly wage in the SAREG, unemployment rate, and number of potential consultations with general practitioners (PCGP) per inhabitant per year. The third group encompassed variables related to the type of supply and demand of veterinary health care, e.g., the proportion of municipalities in a SAREG with territorial specialization in dairy or beef cattle farming, the average size of veterinary clinics, and a dummy variable indicating whether the region shares a border with Belgium—where a number of Belgian veterinarians practice.

Empirical models

Modeling approach

In health economics, spatial econometrics is increasingly used due to the presence of spatial aspects in data (Baltagi et al., 2018). This is notably evident in primary care services (Mobley et al., 2006), quality levels of hospital services (Gravelle et al., 2014), and health expenditures (Moscone et al., 2007). Analyzing such data without adequately incorporating geographic aspects can result in information loss, specification errors, non-convergent estimations, and inefficiencies.

To ascertain whether data required specific spatial data treatment, we must test for the presence of a spatial effect. Spatial econometric models should be considered when the hypothesis of no spatial effect is violated. Spatial effects have two distinct forms: spatial dependence and spatial heterogeneity, which may coexist and should be addressed separately.

Spatial heterogeneity manifests a structural break in the data over space, presenting distributions in various subregions. This can be observed in the form of non-constant error variances in a regression model (heteroscedasticity) or through spatially varying regression coefficients (Le Gallo, 2021). Spatial heterogeneity generally arises from insufficient information in data to identify processes that led to the observed patterns. Techniques from classic non-spatial econometrics can be used to address spatial heterogeneity.

To address spatial heterogeneity, we used regional fixed effects designed to capture unobservable and common factors affecting veterinarian shortage. This involves a dummy variable for administrative regions in France to account for region-specific effects such as regulations and local public policies.

In addition, spatial dependence or spatial autocorrelation denotes the similarity in values with similarity in location (Anselin & Bera, 1998). Until 2007, spatial econometricians mainly focused on models with one type of spatial effect (Elhorst, 2010): the spatial autoregressive lag model (SAR) which contains a spatially lagged dependent variable, and the spatial error model (SEM) which incorporates a spatial autoregressive process in the error term. However, after 2007, Harry Kelejian and James LeSage advocated for models including "spatially lagged dependent variable and a spatially autocorrelated error term" (Spatial Durbin Error Model) or a model with spatially lagged dependent variable and spatially lagged explanatory variable known as Spatial Durbin Model (SDM) (James LeSage, 2009). LeSage demonstrated that SDM "enables derivation of consistent estimates of regression coefficients in the presence of spatially autocorrelated omitted variables." Fingleton and Le Gallo reported that SDM allowed reducing the finite sample bias of endogeneity implied by measurement error and simultaneity (Fingleton & Le Gallo, 2010).

Econometricians often hesitate between starting from the simplest model to the most general (Florax et al., 2003) or from the most complex to the simplest (James LeSage, 2009). In the present study, we followed Elhorst's procedure that summarizes a contemporary state of applied spatial econometrics (Fig. 2).

Elhorst suggested progressing from the simplest model, starting with a basic OLS model:

$$y = X\beta + \varepsilon \tag{4}$$

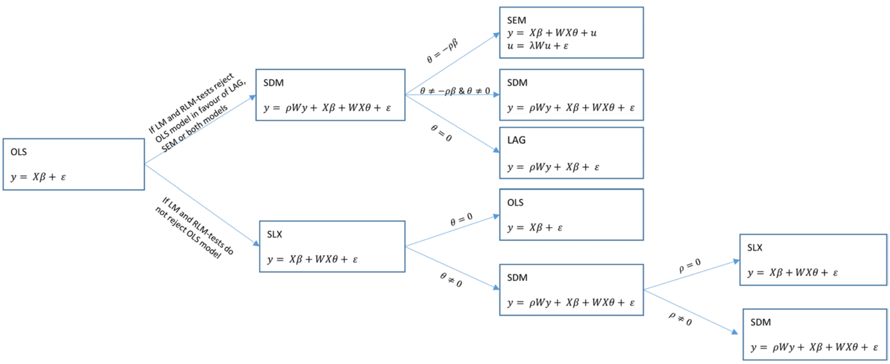

Fig. 2 Elhorst's strategy to test for spatial spatial interaction effects on cross-sectional data

where y is the outcome of interest (share of underserved farms in a SAREG), X a matrix of explanatory variables including a constant, ε an error term, and β a vector of parameters. Then, we test whether the model needs to be extended with a spatial error model, spatial lag model, or spatial independent lagged model. To do so, we used a Moran Index that assesses spatial autocorrelation in residuals of OLS estimates. If the hypothesis of no spatial autocorrelation was rejected, we assessed the type of spatial dependence in the data according to classic likelihood-based test statistics, e.g., likelihood ratio and Lagrange multiplier (Anselin, 1988; Anselin et al., 1996).

If these tests rejected an OLS model in favor of spatial lag, spatial error model, or both models, it is recommended to not conclude too quickly, but to consider estimating a spatial Durbin model:

$$y = \rho \mathrm{Wy} + X\beta + WX\theta + \varepsilon \tag{5}$$

where ρ is a spatial autoregressive parameter indicating the magnitude of the interaction among SAREG through the veterinarian shortage, and W is a non-negative matrix that allows us to model the spatial relationship. This relationship has to be selected among contiguity, inverse distance matrix, k nearest neighbors… Wy represents the endogenous effects among the dependent variables, whereas WX signifies the exogenous effects among the independent variables;ε are independently and identically distributed error terms, whereas θ, as for β, represents a vector of unknown parameters.

After evaluating the SDM model, we tested two hypotheses: $H_0 : \theta = 0$ (LR-LAG test) and $H_0 : \theta + \rho\beta = 0$ (LR-SEM test) with a maximum likelihood ratio test. The rationale was to ensure that the SDM cannot be simplified; in such a case, the simplified model would be preferred, on the principle of parsimony. If the first hypothesis was not rejected, the SDM can be simplified to a LAG model, with the condition that LM tests pointed also to the LAG model. If the second hypothesis was not rejected, SDM can be simplified to SEM with the condition that the LM test points also to a SEM model. However, if both hypotheses were rejected, SDM is the appropriate model for the data.

If an OLS model is not rejected at the beginning, we include spatially lagged independent variables (WX) or a selection of K variables. If the hypothesis $H_0 : \theta = 0$ cannot be rejected, then the OLS model is selected. However, if this hypothesis was not rejected, we estimated SDM and tested $H_0 : \rho = 0$. If the latter hypothesis was rejected, the SDM model was selected; otherwise, an SLX model best described the data.

Spatial weight matrix

In spatial econometrics, the spatial weight matrix W cannot be estimated and must be specified. The selection of the spatial autocorrelation model does not rely on any assumption about the specification of the W matrix. However, careful attention is required in choosing an appropriate W matrix (Leenders, 2002), as misspecification of the weight matrix can have a substantial impact on the derivation of the coefficients of spatial dependence and additional terms in the model (Florax & Rey, 1995). Therefore, we assessed the robustness of results to the specification of W by comparing various weight matrices (e.g., rook contiguity, queen contiguity, and inverse distance). The Akaike Information Criterion (AIC) is a reliable criterion for selecting an appropriate spatial weight matrix (Herrera et al., 2019), but in the veterinarian shortage context, the inverse distance matrix is preferred as it is relevant for assessing spatial accessibility between livestock farms and veterinary services. Indeed, spatial accessibility to veterinary health care is intrinsically linked to the distance traveled by car, which is better represented by the inverse distance matrix than by the contiguity matrices.

Lisa cluster map

Measuring and visualizing spatial autocorrelation allows us to look at similarities in values that are near each other. While measures of global spatial autocorrelation as Moran Index assess spatial correlation on a global level (e.g., country level), the local indicators of spatial association (LISA), which is the local version of the Moran's Index, identifies spatial patterns and clusters within specific localities (Anselin, 1995). The LISA identifies hotspots (or "High-High" type) representing areas where higher values are surrounded by higher values, coldspots (or "Low-Low" type) representing areas where lower values are surrounded by lower values, and spatial outliers ("Low–High" or "High-Low" types) where areas with high (respectively low) values are surrounded by neighbors with low (respectively high) values. The spatial relationships are defined by a spatial weight matrix. The spatial distribution of LISA statistics is illustrated in the Lisa Cluster Map with only significant statistics ($p<0.05$).

Impact measure

Due to the inclusion of a spatial lag term in the SDM and LAG models, estimation results do not directly reflect the marginal effect of variables and require the calculation of impact measures. Hence, it is suggested to employ a partial derivative approach to segregate the estimated coefficients into their respective direct and indirect impacts (James LeSage, 2009).

The direct effect reflects the impact of an independent variable X of unit i on the dependent variable y in the same unit i, without accounting for feedback effects via neighboring units. The spatial indirect effect arises from the impact of independent variables in neighboring regions of region i on the dependent variable of unit i.

Results

Descriptive statistics

THe percentage of livestock units in the cattle sector and revenue for rural veterinarians across all administrative regions in France are in Table 1. As *départements*

Table 1 Regional descriptive statistics

Administrative regions	% of livestock units in cattle sector
Auvergne-Rhône-Alpes	12.1
Bourgogne-Franche-Comté	10.7
Bretagne	11.9
Centre-Val de Loire	3.4
Corsica	0.3
DROM	Not available
Grand-Est	9.2
Hauts-de-France	6.1
Ile-de-France	0.4
Normandie	11.8
Nouvelle-Aquitaine	13.1
Occitanie	7.4
Pays de la Loire	13.1
Provence-Alpes-Côte d'Azur	0.4

et régions d'outre-mère (DROM) are overseas territories and Corsica is an island, these isolated regions were excluded from this study. However, these excluded regions have an insignificant share of livestock units in the cattle sector and negligible revenue for rural veterinarians (Table 1).

Summary statistics for all dependent and explanatory variables in 2019 in France, excluding the two administrative regions that have been deleted, are in Table 2. As a part of the preliminary spatial analysis, a LISA cluster map (Anselin, 1995) (Fig. 3) offered insights into the spatial distribution of the veterinarian shortage. Notably, the diagonal area linking the Grand-Est region to Nouvelle-Aquitaine, the Bretagne region in the North-West and PACA in the South-Est were characterized as "High-High" type, indicating significant spatial clustering of high values of veterinarian shortage in these regions. Conversely, the South-Ouest, the Est (Savoie and Haute-Savoie), and the North (Pas-de-Calais and la Somme) were identified as "Low-Low" indicating significant spatial clustering of low values of a veterinarian shortage. Interestingly, there are very few regions with "Low–High" or "High-Low" designation, indicating associations between dissimilar values. This map highlighted clear and significant spatial clustering patterns, suggesting a tendency for similar values (either high or low) to cluster together in our data.

This map visualizes the LISAsignificant statisticsof the percentage of underserved farms. It illustrates the local spatial autocorrelation between SAREGs. Source: author's calculation using R software.

Spatial autocorrelation test and model selection

In the initial step, we added to all our models a vector of administrative regional dummies to address heterogeneity by capturing unobservable variables.

Table 2 Descriptive statistics of dependent and independent variables

	Definition	Mean	SD	Min	Median	Max
Dependent variable						
Veteterinarian shortage	Percentage of underserved farms in a SAREG	0.62	0.27	0	0.66	1
Independent variables						
Altitude	Average altitude in meters	297.56	303.93	4.83	194.8	1924.33
Coastal	A dummy variable indicating if the SAREG is coastal	0.28	0.45	0	0	1
Urban	A dummy variable indicating if the SAREG contained a major urban area according to INSEE definition	0.12	0.22	0	0.02	1
PCGP	Potential consultations with a general practitioner per inhabitant per year	3.13	0.8	0.38	3.1	6.614
Unemployment	Unemployment rate	6.9	1.39	4.1	6.7	11.7
Wage	Logarithm of the average hourly wage of executives/managers in a SAREG	24.12	1.81	16.7	24.13	32.5
LU	Livestock units in cattle sector	17,687	29,873	8	5983	234,652
FTE	Full-time equivalents dedicated to cattle sector	3.32	4.98	0	1.45	37
Clinic size	Average size of veterinary clinics in a SAREG	2.12	1.31	0	2.10	13
Intensive farms	Percentage of farms with a cattle population exceeding the third quartile	0.24	0.17	0	0.23	1
Belgian border	A dummy variable indicating whether the region shares a border with Belgium	0.16	0.37	0	0	1
Beef	Percentage of municipalities specialized in beef cattle according to MSA	0.07	0.15	0	0	1
Dairy	Percentage of municipalities specialized in dairy cattle according to MSA	0.02	0.07	0	0	1

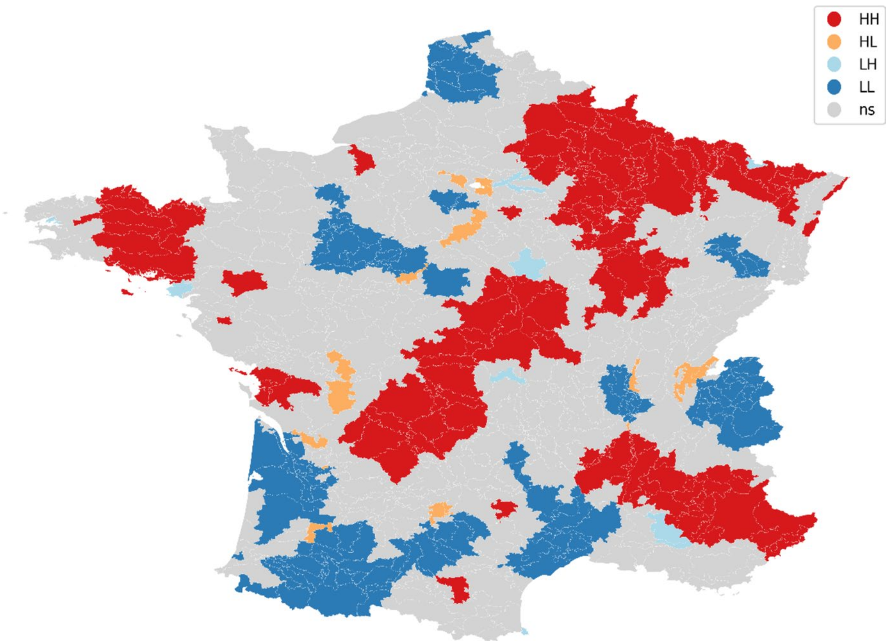

Fig. 3 LISA cluster map of veterinary shortage

Following the outlined procedure in Fig. 2, we started with an OLS model (3). A Moran test was conducted to detect spatial autocorrelation. For this, a spatial weight matrix must be specified. In the absence of prior knowledge regarding the optimal weight matrix and to ensure robust results, a Moran test was performed for various spatial weight matrices (Table 3). All tests consistently rejected the null hypothesis of no autocorrelation ($p < 0.01$), indicating a significant positive spatial autocorrelation. Additionally, we performed LM tests and RLM tests for various weight matrices that consistently pointed to the LAG model. Specifically, SEM was pointed only for weight matrices based on 10 or 15 nearest neighbors. Following Elhorst's procedure (summarized in Fig. 2) and considering the

Table 3 Autocorrelation tests

Weight matrix	Moran I	LM Error	LM Lag	RLM Error	RLM Lag
Queen	0.318***	165.771***	199.975***	0.031	34.234***
Rook	0.318***	165.386***	200.532***	0.009	35.155***
Inverse distance	0.346***	175.991***	219.77***	0.121	43.899***
5-nearest neighbors	0.328***	186.94***	223.627***	0.998	37.685***
10-nearest neighbors	0.257***	225.911***	253.916***	9.523***	37.527***
15-nearest neighbors	0.203***	210.114***	241.658***	12.505***	44.049***

Table 4 Tests if the SDM model can be degraded to LAG or SEM model

Weight matrix	LR SDM-OLS	LR-lag	LR-error test
Queen	144.02***	35.01***	46.56***
Rook	144.55***	35.06***	47.02***
Inverse distance	132.78***	44.64***	56.41***
5-nearest neighbors	155.25***	47.42***	69.98***
10-nearest neighbors	129.9***	47.24***	54.45***
15-nearest neighbors	96.07***	45.54***	45.91***

rejection of the null hypothesis of no autocorrelation along with the results of LM tests and RLM tests favoring the LAG model, we proceeded to estimate SDM (4).

Based on the LR-lag and LR-error tests statistics (Table 4), null hypotheses suggesting that SDM should be simplified to the LAG model or to SEM were consistently rejected at the 1% significance level for all weight matrices. These findings underscored that the SDM model was more appropriate than either the LAG model or SEM, irrespective of the selected weight matrix. Regarding the choice of weight matrix, once the SDM model was identified as most suitable, we further selected the optimal spatial weight matrix based on goodness of fit using the Akaike Information Criterion (AIC). The inverse distance matrix was the most suitable weight matrix in terms of goodness of fit (Table 5).

Regression results

To estimate the marginal effect of the explanatory variable, a partial differential method was used to measure direct, indirect, and total effects (Table 6), according to Lesage and Pace's book (James LeSage, 2009). The spatial autoregressive parameter ρ was positive and strongly significant with a coefficient of 0.56, underscoring the strength of interactions between neighboring small agricultural regions (SAREG) via the veterinarian shortage. The mechanism underlying this spatial correlation will be explained later.

Socio-economic variables were significant factors influencing the veterinarian shortage (Table 6). As expected, an increase of 1% in *unemployment* had the expected positive effect (+4.87%) on the veterinarian shortage, but it did not exert an indirect effect. Conversely, *wage* had no significant direct effect, but exhibited a significant and negative indirect effect, suggesting that a rise of 1% in *wage* (variable expressed in logarithmic form) in neighboring SAREGs was associated with a decrease (−0.96%) in the veterinarian shortage. The coefficient for *PCGP* indicated

Table 5 AIC of SDM according to weight matrices

	Queen	Rook	Inverse distance	5-nearest neighbors	10-nearest neighbors	15-nearest neighbors
SDM	−271.29	−272.41	−286.51	−269.56	−243.83	−213.74

Table 6 Impact measures (direct, indirect, and total effects) of variables in the SDM model with inverse distance weight matrix

Dependent variable: % underserved farms between 0 and 1	Direct	Indirect	Total
Unemployment	0.0487*** (0.0122)	− 0.0285 (0.0237)	0.0201 (0.0222)
Wage	− 0.1368 (0.1168)	− 0.9477** (0.4299)	− 1.0845** (0.4789)
Potential consultations of general practitioner (PCGP)	− 8e − 04 (0.0115)	− 0.1315*** (0.042)	− 0.1323*** (0.0458)
Altitude	1e − 04 (1e − 04)	0 (1e − 04)	0 (1e − 04)
Coast	− 0.0349 (0.0398)	0.0167 (0.0678)	− 0.0182 (0.0603)
Urban	− 0.0854* (0.0463)	0.1828 (0.1493)	0.0974 (0.1633)
Full-time equivalent (FTE)	3e − 04 (0.001)	6e − 04 (0.0036)	9e − 04 (0.0041)
Intensive farms	0.1375** (0.0613)	0.5062*** (0.181)	0.6437*** (0.1932)
Belgian border	− 0.1863*** (0.0656)	0.0867 (0.1203)	− 0.0995 (0.1142)
Beef	− 0.1609* (0.0833)	− 0.3518** (0.1789)	− 0.5127*** (0.1713)
Dairy	0.2611** (0.1114)	0.0889 (0.3999)	0.35 (0.4562)
Observations	701		
Regional dummies	Yes		
Rho	0.56***		
σ^2	0.03***		
R-squared	0.54		

Standard errors are given in the parenthesis

***Coefficients are statistically significant at 1%

**Coefficients are statistically significant at 5%

*Coefficients are statistically significant at 10%

that an increase in access to a general practitioner by 1 unit (having one additional consultation on average per year) in neighboring regions decreased the veterinarian shortage (− 13%), although its direct effect was not significant.

Coefficients associated with amenities were weakly significant. Specifically, the direct effect of *urban* was significantly negative (10% level), indicating that being in an urban region reduced the veterinarian shortage by 8.5% due to the attractiveness of such territories. However, the direct effects of *altitude* and *costal* were not significant. Furthermore, indirect effects of *coastal*, *urban*, and *altitude* were also not significant, suggesting that the influence of neighboring SAREG through these variables was not statistically significant.

Regarding variables related to the type of supply and demand of animal health care, *LU* had no significant effect, neither direct nor indirect. Furthermore, due to a high correlation between *LU* and *FTE*, both variables were not included in the same model. The same model was run by replacing *LU* by *FTE* (see ST1). Similar to *LU*, the variable *FTE* had no significant effect, confirming that the quantity of demand and supply of veterinary health care had no impact on the veterinarian shortage. We also replaced *LU* by *clinic size* in order to test whether a larger structure is associated with a decrease in the veterinarian shortage (ST2), but this variable had no significant effect. However, the type of demand for *dairy* was associated with a high veterinarian shortage, whereas the opposite was observed for *beef*. Additionally, *intensive farms* were positively related to the veterinarian shortage. As expected, the *Belgian border* was associated with a decrease in the veterinarian shortage. The spatial lag terms of these variables were not significant, implying that these variables did not have an indirect effect, except *intensive farms*, which was significantly associated with an increase in the veterinarian shortage in neighboring regions.

Robustness check To assess the robustness of our results, we initially compared coefficients of SDM, LAG, and SEM; there was stability in the results in terms of sign and level of coefficients for direct effects, with the exception of the wage variable. In the LAG model, *wage* had a negative and significant direct effect, whereas it had no significant effect in SDM or SEM models (ST3).

Regarding indirect effects, variables such as *unemployment*, *PCPG*, *urban*, *Belgian boarder*, and *dairy* had significant indirect effects in the LAG model, contrasting with the SDM model. Therefore, the LAG model may overestimate the indirect effect of these variables.

Secondly, in this study, we considered an underserved area in accordance with the official decree, i.e., with < 1 FTE available and accessible for 5000 LU (see the "Share of underserved farms" section). To assess the robustness of our findings, we tested two alternative specifications for the dependent variable by varying this threshold. We considered an underserved area as an area with the following: (i) < 0.75 FTE available and accessible for 5,000 LU and (ii) < 1.25 FTE available and accessible for 5000 LU. The results of the analysis were robust under these specifications and are reported in ST4.

Thirdly, we tested two other specifications of the spatial weight matrices: queen contiguity and rook contiguity. The analysis produced consistent results under these two specifications, except for *wage* that had an insignificant indirect effect in the model with queen and rook contiguity spatial weight matrix (ST5).

Discussion

This study aimed to identify the main determinants of the veterinarian shortage within the cattle sector in France, with the objective of assisting public authorities in designing evidence-based policies. A spatial econometrics approach was employed, leveraging various data sources related to the supply and demand of veterinary care within the cattle sector, socio-economic variables, and territorial characteristics at the level of small agricultural regions.

Considering the criterion used by the French Ministry of Agriculture to define sufficient accessibility to veterinary care in the cattle sector, i.e., one available and accessible full-time equivalents (FTE) dedicated to the cattle sector for every 5000 livestock units (LU), the 12.5 million LU in the French theoretically require at least 2500 FTE. Currently, there are 4443 FTE dedicated to the cattle sector in France, seemingly sufficient to meet the demand. However, when accounting for spatial accessibility of farms to veterinary clinics, 62% of farms are in a veterinarian shortage situation (Table 1). This underscores that the veterinarian shortage is a matter of territorial inequality and uneven distribution of veterinary services.

The veterinarian shortage is inherently a spatial phenomenon, and modeling it necessitates consideration of its spatial interactions. Following Elhorst's strategy, the Spatial Durbin Model was selected to delve into determinants of the veterinarian shortage.

Our regression results lead to four key conclusions. Firstly, we demonstrated a strong spatial dependence of the veterinarian shortage with an autoregressive coefficient of 0.56 (Table 2). This result was attributed to the following: (i) the tendency of veterinarians to consistently settle near their peers (Olfert et al., 2012), creating clusters of areas with more veterinarians relative to demand, and (ii) interdependence between farms where neighbors are likely to be homogeneous in terms of system and production sectors (Storm et al., 2015).

Secondly, the socio-economic variables, namely the *wage*, *unemployment*, and the potential consultations of general practitioners per inhabitant per year (*PCGP*), had a crucial role in explaining the veterinarian shortage. These variables suggested that dynamic areas are more appealing for veterinarians who prefer settling in areas with a larger labor force—which can increase the probability for their spouse to find employment—and with high access to health care and urban amenities, as reflected by *PCGP*. However, these variables had different dynamics. The direct impact of increasing *unemployment* was significant, indicating that an increase in unemployment in SAREG i increases the veterinarian shortage in the same location. Yet, the indirect effect of increasing unemployment was not significant, suggesting that rising *unemployment* in neighboring SAREG i had no impact on the veterinarian shortage in SAREG i. Conversely, PCGP and *wage* variables had a significant indirect (spillover) effect but no direct effect. The negative association between *wages* and the veterinarian shortage aligned with Truchet (Truchet et al., 2017), whereas the positive association between the unemployment rate and the veterinarian shortage has been described (Olfert et al., 2012).

While the coefficients of the variable *unemployment*, *PCGP*, and *wage* have the expected sign, determining why these effects are direct or indirect remains challenging. One possible explanation is that employment often exerts a localized effect, as spouses of veterinarians may seek jobs near their residences to minimize commuting time and costs. By contrast, *PCGP* and *wage*, which reflect the broader quality of life indicators, are important to have in the surrounding areas but not necessarily within the SAREG. Further studies are needed to confirm this reasoning. Thirdly, the analysis of the coefficients of the variables related to supply and demand of veterinary health care reveals that the type of demand for veterinary healthcare is more responsive to the veterinarian shortage than the quantity of supply or demand of veterinary health care. The coefficient linked to the number of full-time equivalent veterinarians dedicated to the cattle sector was not significant (Table 2). This implies that the veterinarian shortage, based on both the quantity of veterinary health care supply and demand, did not exhibit a clear linear relationship with them. We also tested whether the agglomeration of veterinarians reduced the veterinarian shortage by looking at the effect of the average size of veterinary clinics (Table ST2). It was expected that larger veterinary structures reduce their production costs and thereby allow veterinarians to provide care under better conditions. But the *clinic size* variable had no significant effect. This is due to the fact that veterinarian shortage is not only a matter of resources allocated by the veterinary clinics but also of accessibility. Indeed, while a large veterinary structure may benefit from agglomeration effects, the advantage of having several smaller veterinary clinics is that they are more spatially distributed across the territory and are more accessible for farmers. Instead, it was the type of demand—*intense farming*, *beef* and *dairy*—that had significantly negative, negative, and positive effects, respectively, on the veterinarian shortage. This result, indicating veterinarians' preferences for areas specialized in beef rather than the dairy sector, aligns with Truchet's findings. However, it diverges as regions specialized in the dairy sector were insignificant in her study, whereas in our research, they were significant and positively correlated with the veterinarian shortage. We identified two reasons why veterinarians are discouraged from settle in these regions: (i) the dairy sector underwent significant changes since 2008 and faced many challenges (Dervillé & Allaire, 2014) and (ii) dairy cows, due to their intensive milk production, are more exposed to diseases, infections as mastitis, and reproductive issues, necessitating more frequent veterinary care. Furthermore, the variable *Belgian border* indicated that being close to the Belgium border was associated with a decrease in the veterinarian shortage by 10%. We included this control variable to capture the phenomenon of a high rate of veterinarians graduating from a Belgian veterinary school in the northeast of France (Conseil national de l'Ordre des vétérinaires, 2021). Considering this variable is crucial because it explains why the northeast region of France has a better supply of veterinarians and experiences fewer veterinarian shortages, *ceteris paribus*, compared to regions that are equally attractive from a socio-economic standpoint.

Fourthly, the influence of territorial and geographical characteristics on veterinarian shortage is limited, as *altitude* and *coastal* had no significant effect. However, urban regions were associated with a decrease in veterinarian shortage compared to medium-sized urban centers and remote rural areas. This confirmed that among amenities, living zones had a significant impact on the attractiveness of veterinarians, consistent with Truchet's results except that *altitude* in our study had no significant effect.

By using a veterinarian shortage indicator via the 2SFCA, this study contributes to a more nuanced understanding of the factors driving inequalities in access to care, rather than merely describing the spatial distribution of veterinarians (Truchet et al., 2017). Most existing reports on veterinarian shortage are either descriptive or qualitative. In this article, we aimed to employ econometric tools to quantify the effects of socio-economic factors on veterinarian shortages. Moreover, the spatial econometric approach allowed us to control for spatial effects by accounting for spatial heterogeneity between administrative regions and estimating the spatial autocorrelation of veterinarian shortages. This can offer insights to explain the results of previous studies that evaluated the effectiveness of public policies combatting veterinarian shortage (Berrada et al., 2024).

However, this study had two limits. First, we faced data constraints, as we did not use some economic data that could have been important, such as the cost of veterinary care, to capture inter-regional disparities that may reveal the elasticity of demand. Regions with a low supply of veterinary services are expected to have higher prices, which can influence the level of veterinarian shortage. Since we do not have data on veterinary care prices, we only evaluated the impact of supply (represented by full-time equivalents) in a region, which was not significant (Table 6). Similarly, on the supply side, we were unable to include veterinarians' remuneration and salaries, which can affect the attractiveness of certain territories to practitioners. These data are only available at a level of aggregation too broad to allow their incorporation into our model. Second, this study remains static, due to a lack of data, whereas it would be valuable to study the factors of veterinarian shortage using a dynamic approach with spatial panel models.

Conclusions

Our findings provided a preliminary understanding of factors contributing to veterinarian shortages in rural areas, leading to recommendations for policymakers. First, even though veterinarians in FAS are required to settle in rural areas to meet the demand, they prefer to practice near urban locations that are more attractive. This preference is partially due to the fact that rural areas have inadequate public services, making them less attractive places to live and work. Thus, enhancing public services in rural areas should be considered to retain veterinarians. Second, as veterinarian shortage is more prevalent in economically disadvantaged regions, it would be more judicious to encourage veterinarians to establish their practices in rural areas rather than increasing the number of veterinary students admitted, which does not ensure that they will settle in these underserved areas after they graduated (Lambert, 2022). Third, we have identified two gaps in the literature that need to be addressed by policymakers to enable more effective interventions. The first gap pertains to the limited attempts to evaluate the effects of public policies implemented to counter the veterinarian shortage and to identify the most effective veterinarians' incentives to practice in rural areas. A parallel gap is observed in healthcare professions (Grobler et al., 2015). For example, one could assess the impact of selecting students with rural backgrounds for admission to the national veterinary schools, as they are more likely to work in rural areas after graduation (Sans et al., 2011; Villarroel et al., 2010). However, it is important to address this issue with caution to circumvent pitfalls encountered with quota systems. The second gap concerns the impact of the veterinarian shortage on (i) the decline of cattle populations and (ii) health issues. Further investigations should be conducted to provide a more accurate assessment of the extent of the veterinarian shortage impacts, allowing public authorities to quantify the damages that are currently only observed but not measured. This would ensure the allocation of appropriate resources to address the veterinarian shortage effectively.

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MB: methodology, software, formal analysis, data curation, writing—original draft preparation.

DR: validation, investigation, resources, writing—review and editing, supervision, project administration.

GL: validation, investigation, writing—review and editing, supervision, project administration.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability The analyses presented in this study were conducted using the R software. Specifically, the “spatialreg” and “spdep” packages were employed to implement spatial regression models and spatial dependency tests, respectively. The R scripts utilized for data analysis and the generation of results are available from the corresponding author upon reasonable request.

Declarations

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